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Abstract

Describes a computer program (Fortran IV language) designed to analyze hydrographs. Using only input data of stage and time, the program automatically determines the beginning and end of each event, analyzes each event with respect to all its hydrologic characteristics (including a partitioning of base flow, interflow, and rapid flow), and then prints a detailed analysis of each event and a series of summaries of all events analyzed. The hydrologist can influence the results only by changing the time interval between hydrograph readings. The method has been tested on both simple and complex hydrographs representative of runoff events in many regions of the United States.

INTRODUCTION

A hydrograph is a curve depicting a stream's rate of flow throughout a given period of time. If the records are complete, the curve is continuous; this curve reveals to the trained observer the innermost secrets of a watershed's behavior — nothing is concealed. Every change in the curve reflects the watershed's reaction to a multitude of internal and external forces. A steep rise in the curve could reflect the passage of a high intensity storm; a gradual descent might reflect the watershed's high water storage capacity. Every change in the hydrograph can be readily interpreted in the light of forces acting on the watershed. A study of all changes in the hydrograph is a key to our understanding of the functioning of a watershed.

Streamflow is one of the end products of precipitation that falls on a watershed. Some of this precipitation falls directly into the stream channel and brings about an immediate rise in the rate of streamflow. Similarly, another portion of the precipitation quickly enters well defined channels; it also contributes to the rapid rise in streamflow rate. Some of the rain enters the soil mantle, and thence, by circuitous paths, finally enters the stream channel. Another portion, pulled by the force of gravity, finds its way to the water table (the surface of the groundwater), and eventually flows into the stream channel. The shape of the hydrograph is determined by the amount and rate at which each of these components enters the stream channel. This shape is a unique expression of a watershed's reaction to its environment.

Although the ultimate purpose of hydrograph analysis is an understanding of a watershed's behavior, this can be achieved only if we have a thorough understanding of the flow patterns that together make up the hydrograph. For this reason, hydrologists have devised many methods to separate the components, despite the belief that "it is practically impossible to measure the volumes of water following each path . . . ."[1]

The first and most important step in hydrograph analysis is to partition the hydrograph into its components:

Total flow = Base flow + Interflow + Rapid flow

Base flow is the contribution from groundwater — water that moves under differences in head in a saturated zone. Interflow is water that percolates through the soil mantle and, after some delay, enters the stream. Rapid flow (also called surface flow) is water that enters the stream channel with a minimum delay; it includes channel interception. The sum of interflow and rapid flow are designated as stormflow.

The techniques now employed in hydrograph analysis are highly subjective. Moreover, the analyst starts his analysis at the end of the storm hydrograph and proceeds backwards in time towards the beginning of the storm hydrograph.[2] Linsley and others discuss thoroughly the procedures and arbitrary rules that are used in hydrograph separation.

This paper presents a computer program designed to analyze automatically hydrologic

[1] *Ray K. Linsley, Jr., Max A. Kohler, and Joseph L. H. Paulhus. P. 387, in: Applied Hydrology, 689 p. New York: McGraw-Hill Co. 1949.*

[2] *Ibid, Ch. 15.*

events recorded on a hydrograph. These events could result from either, or a combination of, rainstorms, snowmelt, or excessive evapotranspiration. The analytical technique is completely automated; the results are dependent entirely on the flow rates shown on the hydrograph. The hydrologist can influence the results in only one way: by increasing or decreasing the number of sampling points along the hydrograph.

The technique used in the computer program was tested on hydrographs of typical runoff events in many regions in the United States; it was considered successful because the computed separation curves crossed the recession limbs of the hydrographs at their points of inflection.

BASIC ASSUMPTIONS

Two basic assumptions underlie the computations: that both increment in base flow and the ratio of surface runoff to interflow depend essentially on the hydrograph's rate of rise. A rapid rise indicates a proportionately smaller increment in base flow than does a moderate rise. On the other hand, the ratio of surface runoff to interflow is large when the stream rises rapidly; this ratio is small when the stream rises slowly.

We also assume that (a) surface runoff (including channel interception) ends at the first inflection point following peak flow, and that (b) interflow ends at the lower inflection point on the recession limb of a simple hydrograph. Our research was directed towards defining equations that — if based on the first two assumptions — would meet the criteria of the third and that would be applicable to any hydrograph.

ESSENTIAL ELEMENTS OF THE SEPARATION TECHNIQUE

The heart of this program consists of a series of calculations to determine the consecutive positions of points along two curves: the base flow curve (which separates base flow from stormflow) and the interflow curve (which separates interflow from rapid flow.) Figure 1 is used to illustrate the parameters entering the calculation of points along both the base flow and interflow lines.

Base Flow Computations

The rate of flow at any point (P_i) on the base flow line is equal to the sum of the rate at a prior time (P_{i-1}) plus an incremental value (U_i):

$$P_i = P_{i-1} + U_i \tag{1}$$

where

$$U_i = \exp[-(1.0 + \sin A)] \times (\Delta t \times \Delta R \times \tan B)^{1/2} \tag{2}$$

where (see fig. 1)

$$\Delta R = R_i - P_{i-1}$$
$$\Delta t = t_i - t_{i-1}$$
$$A = \arctan (\Delta R / \Delta t)$$
$$B = (H \times A - \Delta R)/H$$
$$H = (\Delta R^2 + \Delta t^2)^{1/2}$$

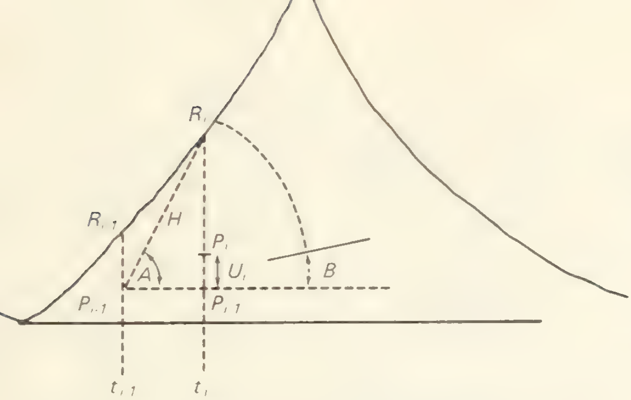

Figure 1. — Parameters used to locate points along the base flow line.

Each successive point on the hydrograph is the basis for a new calculation of P_i. The event ends when the value of a point on the base flow line equals a rate value on the hydrograph trace; i.e., $P_i = R_i$. The next hydrograph event begins when the hydrograph starts to rise again. At that point, $R_{i-1} = P_{i-1}$.

Interflow Computations

The curve that separates interflow from surface flow (which includes channel interception) is similarly computed from point to point. Any point S_i on the interflow curve is equal to the value at a prior time (S_{i-1}) plus an incremental value (W_i).

Thus, $$S_i = S_{i-1} + W_i \tag{3}$$

where

$$W_i = [(\Delta t^2 + \Delta S^2)^{1/2} \times \Delta S]/(\Delta t + K \times \Delta S) \tag{4}$$

where

$$\Delta t = t_i - t_{i-1}$$
$$\Delta S = R_i - S_{i-1}$$
$$K = 3.0$$

Surface runoff ends when the curve intersects the hydrograph; i.e., $S_i = R_i$.

DISCUSSION OF TECHNIQUE

Table 1 shows the results of analyses of hydrographs of representative storms in several regions of the United States. The analyzed hydrographs include both simple and complex hydrographs. Source for the basic hydrograph data is Hobbs and Burford.[3] In all cases, the analyses were performed on data expressed in cubic feet per second (c.f.s.). Data originally expressed in inches per hour were converted to c.f.s. Figures 2 and 3 show the separation, respectively, of a simple and complex hydrograph into its components. The figures show the total flow hydrograph, and the computed interflow and base flow rates.

Normally, on large watersheds, the time interval between sampled points on the hydrographs is one or more hours. Therefore, the analytical results will be independent of the hydrologist. On very small watersheds, the hydrologist tries to reproduce the shape of the hydrograph by sampling at small and variable increments of time because the smaller the time interval used the more accurately can he reproduce the hydrograph's original shape. Thus, on very small watersheds the hydrologist can influence the results by increasing or decreasing the number of sampling points used to reproduce the shape of the hydrograph.

Our analyses show that when we reduced the number of sampling points 75 percent, we changed the computed results by significant amounts. The maximum change was observed on a small watershed (0.07 km.^{2}) from which all runoff ceased after 1.75 hours: computed total flow was increased 0.457 cm. (28 percent); stormflow increased 0.508 cm. (28 percent); and stormflow runoff duration was increased 6.6 minutes. Consequently, the hydrologist who analyzes the hydrographs of

[3] *Harold W. Hobbs and James B. Burford. Hydrologic data for experimental agricultural watersheds in the United States, 1963. USDA Agr. Res. Serv., Misc. Pub. 1164. 1970.*

Table 1. — Analysis of hydrographs of streams in different regions of the United States[1]

	Vero Beach, Florida	Blacksburg, Virginia	N. Danville, Vermont	Hastings, Nebraska	Colby, Wisconsin	Waco, Texas	Reynolds, Idaho
Area (km.^{2})	255.5	6.0	111.1	8.3	1.4	2.3	233.4
			PERCENT OF TOTAL FLOW				
Base flow	32.47	14.80	53.16	9.07	22.74	5.52	13.36
Stormflow	67.53	85.20	46.84	90.93	77.26	94.48	86.64
			PERCENT OF STORMFLOW				
Interflow	65.38	89.99	90.62	66.58	90.41	89.63	93.49
Surface flow	34.62	10.01	9.38	33.42	9.59	10.37	6.51
Before peak	44.19	32.47	37.81	39.92	14.59	26.71	14.68
After peak	55.81	67.53	62.19	60.08	85.41	72.39	85.32
			DURATION (HOURS) OF STORMFLOW				
Time to peak	48.00	1.00	10.08	3.17	4.12	1.23	18.00
Recession time	56.64	3.36	24.88	5.91	8.87	3.89	38.60
Total time	104.64	4.36	34.96	9.08	12.99	5.12	56.60

[1] *Source of data: ibid, text footnote 3.*

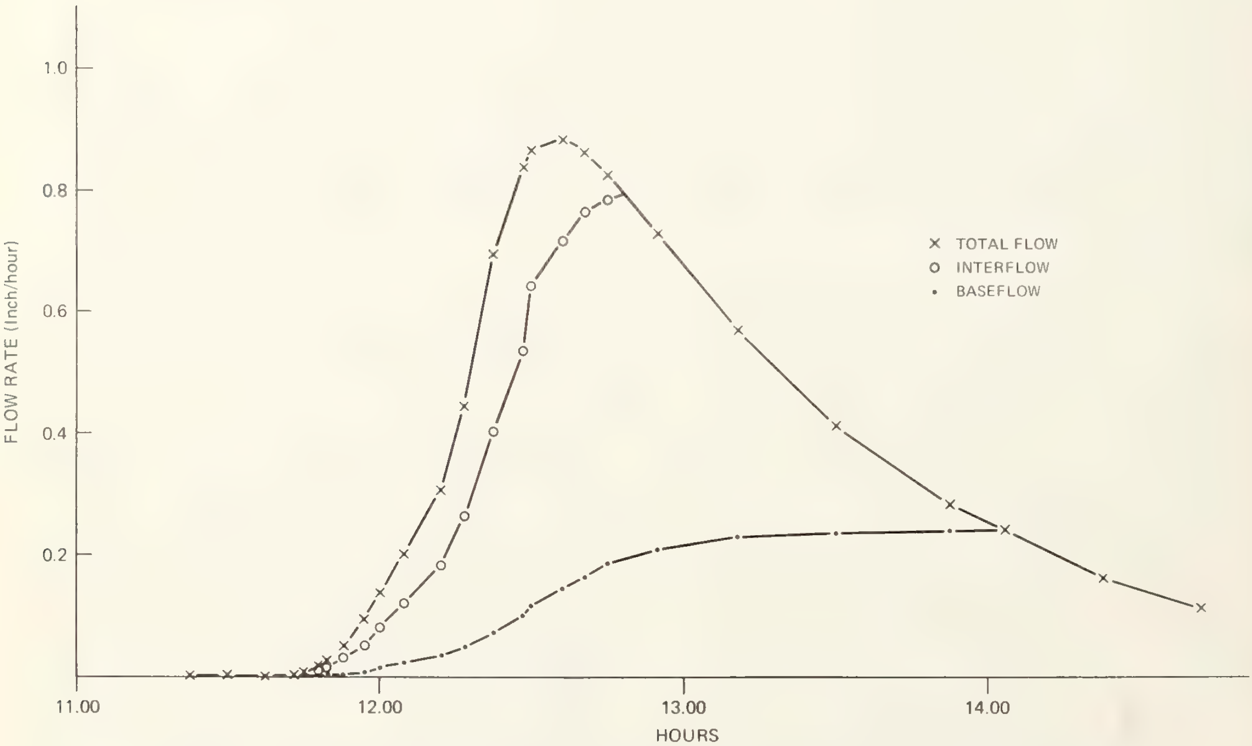

Figure 2. — Flow components in a simple hydrograph recorded at Riesel, Texas.

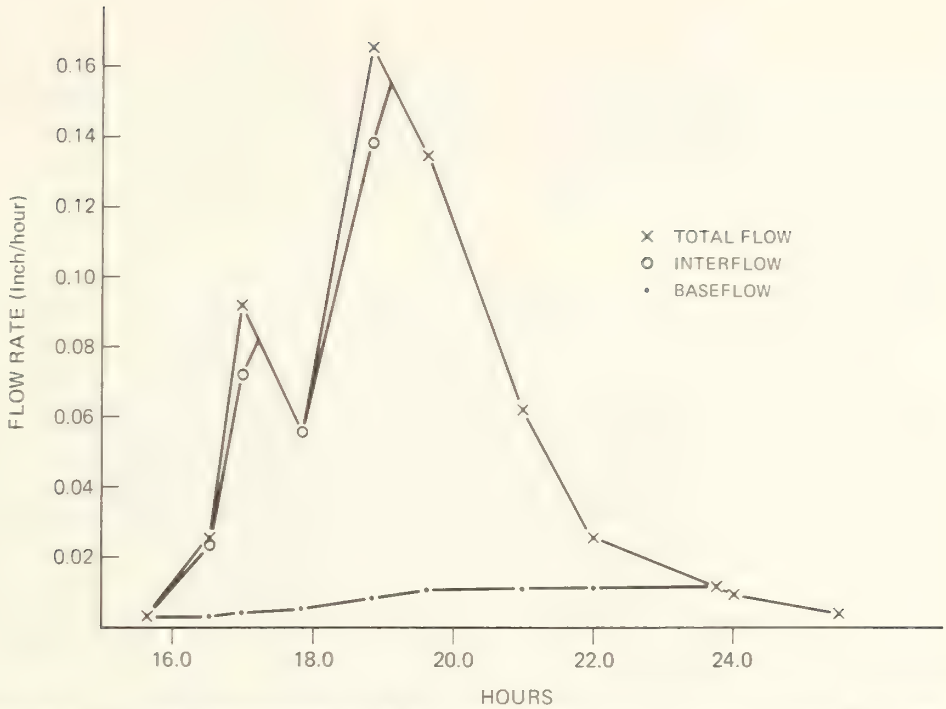

Figure 3. — Flow components of a complex hydrograph recorded at Hastings, Nebraska.

very small watersheds should make every effort to select points that reproduce as accurately as possible the true shape of the hydrograph.

Equation (2) includes two angle measurements *(A* and *B)*. Accordingly, it is apparent that the results of any analysis will depend on the units of measurement, as shown in table 2.

Normally, the analysis would be performed on data expressed in a unit suitable for the watershed: c.f.s. for low water-yielding watersheds, and inch/hour for high water-yielding drainages. Certainly, a great deal of accuracy is lost when calculations are performed on angles measured in minute fractions of a radian. For example: suppose streamflow from a 580-acre (2.346-km.^{2}) watershed is expressed in inches. If the increase is 0.0005 inch in 0.1 hour, angle *A* is approximately 0.005 radian; if expressed in c.f.s., the angle is 1.24 radians. The effect of loss in accuracy as well as the unit of measurement is fully reflected in the last column of table 2, which shows figures for surface runoff based on data expressed in inch/hour.

Equation (4) is used to partition stormflow into surface runoff (including channel interception) and interflow. The equation contains a constant *(K)* to which we assigned a value of 3.0. The exact value of *K* can be determined only if precise data from controlled laboratory or field experiments are available, but we do not have such data.

A change in the value of *K* results in significant changes in the analytical results (table 3). Increasing the value of *K* yields (a) larger computed values for surface runoff; (b) a corresponding decrease in interflow; and (c) a larger computed value for duration of surface runoff. Our analyses for large forested watersheds show that the computed period for surface runoff duration is extended by 1-3 hours if the value of *K* is increased from 3.0 to 4.0.

We believe that the value of *K* is related to the proportion of the watershed represented by the main channel and its tributaries. For any particular watershed, the value of *K* might well change with either or both the season and the characteristics of the storm. This concept of *K* agrees with the concept of a variable source area.[4]

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[4] *John D. Hewlett and Alden R. Hibbert. Factors affecting the response of small watersheds to precipitation in humid areas. P. 275-290, in: Forest Hydrology, edited by William E. Sopper and Howard W. Lull. New York: Pergamon Press, Inc. 1967.*

The assigned value of $K = 3.0$ is acceptable if the hydrologist is mainly interested in the comparative behavior of several watersheds or in the reaction of a single watershed to storms of different magnitude. On the other hand, the precise partitioning of stormflow into surface runoff and interflow will depend on the exact value of K as determined under controlled experiments.

Table 2. — Effect of unit of measurement on results of analysis

Location	Basic hydrograph unit c.f.s.	Basic hydrograph unit inch/hr.	Basic hydrograph unit c.f.s.	Basic hydrograph unit inch/hr.
	Stormflow as % of total runoff		*Surface runoff as % of stormflow*	
Vero Beach, Fla.	67.53	69.80	34.62	0
Blacksburg, Va.	85.20	60.01	10.01	7.89
N. Danville, Vt.	46.84	82.54	9.38	0
Hastings, Neb.	90.93	87.19	33.42	8.14
Colby, Wisc.	77.26	75.12	9.59	0.78
Waco, Tex.	94.48	66.30	10.37	17.99
Reynolds, Ida.	86.64	59.31	6.51	0.37

Table 3. — Effect of K (Equation 4) on surface runoff as percent of stormflow during October-November 1968, in the East Fork Horse Creek watershed, Idaho

Event No.	Stormflow	$K = 2$	$K = 3$	$K = 4$	$K = 5$
	Cubic ft./100				
19	6.7	5.77	8.60	11.33	13.96
4	22.5	1.70	2.55	3.40	4.24
3	68.8	2.17	3.34	4.55	5.81
23	98.9	3.64	5.36	7.10	8.90
1	202.6	0.26	0.38	0.49	0.60
15	308.4	1.54	2.44	3.44	4.53
34	613.2	11.93	18.53	24.63	30.15
28	1873.1	11.79	19.65	27.05	33.63
16	3898.0	11.89	19.95	27.10	33.24

THE COMPUTER PROGRAM

The program consists of three sections: Input of basic data (lines 1 through 12); analysis of data (lines 13 through 129); and output of results (lines 130 through 183).

Input of Basic Data

The program is designed to accommodate data for 1 year, providing the time interval between readings is not less than 1 hour and the number of storm events is not more than 300. The dimension statements should be changed if the number of data points exceeds 9000 or the number of anticipated storm events exceeds 300. If either of these conditions applies, the author suggests that less than a year's data be analyzed at one time.

The "read" statement should fit the format in which the input data are punched on the cards. In this program, there is no "read" statement for *hour*, because all hydrograph readings were taken at 1-hour intervals. If a variable time interval characterizes the input data, then a new "read" statement should be made.

Analysis of Data

1. Volume parameters
   - Total flow
     - Base flow
     - Storm flow
       - Interflow
       - Rapid flow
2. Time parameters
   - Hour at which event starts
   - Hour at which event peaks
   - Hour at which event ends
   - Number of hours from start to peak
   - Number of hours from peak to end (recession time)
3. Rate parameters
   - Initial streamflow rate
   - Peak rate
   - Final rate
4. Angle parameters (in radians)
   - Rising angle (formed by intersection of horizontal line and line connecting initial and peak rates)
   - Recession angle (formed by intersection of a vertical line and line connecting peak and final rates)
   - Top Angle (formed by intersection of line connecting initial and peak rates with line connecting peak and final rates)
   - Base angle (formed by intersection of horizontal line and line connecting initial and final rates)
5. Line parameters
   - Base line (length of line connecting initial and final points of the storm hydrograph)
   - Perimeter (sum of lines connecting initial, peak, and final points on the storm hydrograph.)
6. Ratio parameter
   - Ratio of perimeter to natural logarithm of 1.0 + stormflow)

The relation between stage and flow rate (cubic feet per second) is unique to each type of waterflow-measuring installation. Hence, the user of this program must supply the calibration equation that applies to the installation. This is done in lines 23 and 24, and also in lines 38, 39, and 56. In addition, the user must indicate the area of the watershed in acres (line 164).

Output of Results

Summaries of results of all analyzed storms are tabulated in a series of tables (see Appendix 1) and also on cards. (See Appendix 2, lines 173 and 174, for format.)

Appendix tables 1 through 5 are examples of the program printout. Tables 2-5 are summary tables of all the storms analyzed. Table 1 (Appendix 1) is a detailed analysis of each individual event, and requires some explanation. The sample printout is an analysis of a short storm during October 1968 on the East Fork of Horse Creek in north central Idaho.

The storm started at hour 347 when streamflow rate was 4.139818 c.f.s. (Six decimals are printed to enable the hydrologist to analyze any portion of the event without loss of accuracy due to rounding-off procedures.) The storm ended at hour 361.92 when streamflow rate was 4.335419 c.f.s. Column 2 shows the rate of flow (c.f.s.) at hourly intervals along the base flow line — the line separating base flow from stormflow. The third column ("runoff rate") shows actual streamflow rate (c.f.s.) at hourly intervals. This figure is the input data (stage-in feet) converted to c.f.s. The last column (interflow rate) shows the rate of flow (c.f.s.) at hourly intervals along the line separating interflow from rapid flow. As long as values in this column are *smaller* than those in the "runoff rate" column, the rapid flow separation curve has not crossed the hydrograph. When rapid flow has ended, then the figures in the last column are identical with those in the "runoff rate" column. In this example, rapid flow ended between hours 353 and 354. Total flow from hour 347 to hour 361.92 was 68.413391 c.f.s.-hours (column 5), of which 63.696930 was base flow (column 4) and 4.716461 was stormflow (column 7). Stormflow amounted to 6.89 percent of the total flow (column 6). Other figures in table 1 as well as in the summary tables are self explanatory.

USES FOR THE COMPUTER PROGRAM

Hydrograph analysis is a difficult and time-consuming operation. The inherent difficulties have forced hydrologists to limit their analysis to a few extraordinary hydrologic events, or to events that they believe represent average conditions.

By using this computer program, the hydrologist can analyze all streamflow events — rainstorms, snowmelt events, and even daily events resulting from excessive evapotranspiration. Any event, regardless of its cause, can be analyzed automatically, and can be recorded in a condensed form. The computer program enables the hydrologist to readily compare the numerous elements of hydrologic events occurring on two or more watersheds, because they are recorded in orderly form.

APPENDIX 1

Tables 1 through 5 are examples of the printed output of the program. Table 1 is an analysis of storm No. 6. Tables 2 through 5 are summary tables of 34 storms, which include storm No. 6.

TABLE 1

STORM NUMBER 6

STORM BEGINS AT 347.00 INITIALRUNOFF RATE IS 4.139818

TIME	BASEFLORATE	RUNOFRATE	BASEFLO	TOTALFLO	STORMFLO%	STORMFLO	INTERFLO	RAPIDFLO	INTERFLORATE
348.00	4.141055	4.235245	4.140436	4.187531	1.124695	0.047095	0.036644	0.010451	4.214343
349.00	4.155521	4.526405	8.268724	8.568357	3.263565	0.279633	0.187118	0.092515	4.383182
350.00	4.174996	4.625076	12.453982	13.144097	5.250397	0.690115	0.477149	0.212966	4.527397
351.00	4.208504	4.875252	16.645721	17.894257	6.977310	1.248535	0.902907	0.345628	4.707621
352.00	4.246061	4.976706	20.873001	22.820221	8.532883	1.947220	1.460339	0.486881	4.861808
353.00	4.281388	4.976706	25.136719	27.796921	9.570145	2.660202	2.101425	0.558777	4.947815
354.00	4.305362	4.824818	29.430084	32.697678	9.993362	3.267593	2.694366	0.573227	4.824818
355.00	4.316115	4.625076	33.740814	37.422623	9.838470	3.681808	3.108575	0.573234	4.625076
356.00	4.323717	4.575636	38.060730	42.022964	9.428741	3.962234	3.389014	0.573220	4.575636
357.00	4.326726	4.477373	42.385941	46.549469	8.944321	4.163528	3.590297	0.573232	4.477373
358.00	4.329628	4.477373	46.714111	51.026840	8.451904	4.312729	3.739492	0.573236	4.477373
359.00	4.332428	4.477373	51.045135	55.504211	8.033798	4.459076	3.885838	0.573238	4.477373
360.00	4.335131	4.477373	55.378906	59.981583	7.673492	4.602676	4.029431	0.573245	4.477373
361.00	4.335418	4.379911	59.714172	64.410217	7.290894	4.696045	4.122799	0.573246	4.379911
361.92	4.335419	4.335419	63.696930	68.413391	6.894089	4.716461	4.143235	0.573226	4.335419

TABLE 2

SUMMARY OF STORM DATA

NO	TIME START	TIME PEAK	TIMEEND	R START	R PEAK	R END	STORMFLO	INTERFLO	RAPIDFLO
1	69.0000	118.0000	144.1334	2.4500	2.6077	2.5179	5.6283	5.6071	0.0212
2	165.0000	201.0000	246.7191	2.1088	2.5284	2.3449	10.7387	10.6851	0.0536
3	254.0000	278.0000	291.4971	2.3341	9.8412	6.3394	90.8405	77.1339	13.7066
4	301.0000	303.0000	308.6111	5.1820	5.2858	5.1908	0.6245	0.6086	0.0159
5	327.0000	331.0000	345.2043	4.1398	4.3799	4.1777	1.9108	1.8470	0.0638
6	347.0000	352.0000	361.9185	4.1398	4.9767	4.3354	4.7165	4.1432	0.5732
7	393.0000	422.0000	433.2788	3.2317	3.8124	3.5274	9.3303	9.0223	0.3080
8	443.0000	472.0000	479.4075	3.1885	6.7616	4.5000	27.3900	22.0784	5.3115
9	480.0000	481.0000	562.4644	2.9760	5.1304	4.6021	36.3999	32.9199	3.4800
10	568.0000	572.0000	582.0872	4.5756	4.8753	4.6208	1.6851	1.6027	0.0824
11	591.0000	604.0000	611.7495	4.4774	6.0339	5.0023	10.9402	9.8133	1.1268
12	666.0000	667.0000	673.9541	4.1398	4.1874	4.1420	0.3234	0.3174	0.0060
13	690.0000	701.0000	722.6267	4.0924	4.6747	4.3496	7.2463	6.7678	0.4785
14	779.0000	782.0000	836.1768	3.5847	3.6752	3.6219	3.7770	3.7662	0.0108
15	890.0000	901.0000	916.9890	2.6077	3.2750	2.9356	8.5678	8.3585	0.2093
16	918.0000	942.0000	953.9739	2.9342	14.8462	7.0009	108.2775	86.6776	21.5999
17	957.0000	958.0000	959.4570	6.4219	6.8189	6.4540	0.6103	0.3771	0.2332
18	996.0000	1010.0000	1024.3865	5.0277	7.3424	5.8496	16.6890	13.7689	2.9201
19	1035.0000	1037.0000	1038.2371	5.3380	5.4429	5.3410	0.1861	0.1701	0.0160
20	1042.0000	1044.0000	1046.3083	5.1820	5.2858	5.1860	0.2856	0.2697	0.0159
21	1047.0000	1049.0000	1049.4841	5.0790	5.2858	5.0870	0.2005	0.1553	0.0452
22	1050.0000	1051.0000	1051.9805	4.8753	5.0277	4.8782	0.1481	0.1019	0.0462
23	1053.0000	1059.0000	1066.1768	4.8753	5.3380	4.9588	2.7460	2.5989	0.1472
24	1067.0000	1068.0000	1072.9065	4.8753	5.0277	4.8847	0.5714	0.5191	0.0523
25	1080.0000	1137.0000	1143.0098	4.0452	11.4696	9.1180	102.8784	90.2168	12.6616
26	1162.0000	1195.0000	1207.2866	4.4285	5.6018	5.0131	14.7247	14.3110	0.4137
27	1213.0000	1217.0000	1226.0235	4.8753	5.1304	4.9247	2.0130	1.9556	0.0574
28	1238.0000	1253.0000	1267.4221	4.7245	10.8479	7.0589	52.0298	41.8076	10.2222
29	1305.0000	1311.0000	1326.2224	5.5487	6.4780	5.7924	5.9813	5.3071	0.6742
30	1373.0000	1374.0000	1374.9924	5.3904	5.4429	5.3908	0.0520	0.0449	0.0071
31	1388.0000	1389.0000	1391.4775	5.2858	5.3904	5.2908	0.2789	0.2526	0.0262
32	1399.0000	1400.0000	1400.3293	4.3315	4.3799	4.3322	0.0320	0.0279	0.0041
33	1401.0000	1407.0000	1416.1445	4.2352	5.3904	4.6037	7.6906	6.7187	0.9719
34	1421.0000	1428.0000	1450.3252	3.9982	6.5344	4.8985	17.0336	13.8773	3.1563

TABLE 3

STORM NO	STORMFLO BASE LINE	PERIMETER	TOP ANGLE	TIME TO PEAK	STORMFLO	PERIMETER/ LN(1+STORMFLO)	RECESSION TIME	BASE LINE ANGLE	RISING LIMB ANGLE	FALLING LIMB ANGLE
1	75.133377	150.267151	3.134936	49.000000	5.628342	79.449478	26.133362	0.000904	0.003219	1.567360
2	81.719391	163.441254	3.125924	36.000000	10.738663	66.361618	45.719055	0.002889	0.011654	1.566782
3	37.710373	76.800995	2.584583	24.000000	90.840500	16.991165	13.497070	0.106411	0.303153	1.316941
4	7.611089	15.225668	3.072803	2.000000	0.624496	31.380310	5.611084	0.001156	0.051857	1.553864
5	18.204376	36.417358	3.067404	4.000000	1.910767	34.085373	14.204346	0.002080	0.059951	1.556560
6	14.919739	29.928452	2.911185	5.000000	4.716461	17.167206	9.918457	0.013111	0.165840	1.506229
7	40.279892	80.568100	3.096311	29.000000	9.330338	34.503281	11.278809	0.007342	0.020021	1.545536
8	36.431076	73.395386	2.722670	29.000000	27.389969	21.935013	7.407471	0.036006	0.122593	1.274467
9	82.480347	166.321472	1.998897	1.000000	36.399902	45.923996	81.464355	0.019716	1.136209	1.564311
10	14.087230	28.188797	3.041603	4.000000	1.685089	28.539429	10.087158	0.003204	0.074764	1.545572
11	20.756149	41.666870	2.890079	13.000000	10.940155	16.801773	7.749512	0.025294	0.119169	1.438452
12	7.954102	15.909483	3.087484	1.000000	0.323395	56.778961	6.954102	0.000274	0.047573	1.564262
13	32.627716	65.272263	3.073669	11.000000	7.246262	30.938248	21.626709	0.007881	0.052887	1.555761
14	57.176773	114.354904	3.110479	3.000000	3.776962	73.126068	54.176758	0.000649	0.030128	1.569812
15	26.990997	54.003830	3.059772	11.000000	8.567810	23.912384	15.989014	0.012148	0.060592	1.549568
16	36.203003	77.311691	2.100856	24.000000	108.277496	16.470703	11.973877	0.112568	0.460711	0.990772
17	2.457241	5.035198	2.518267	1.000000	0.610332	10.568375	1.457031	0.013062	0.377924	1.325395
18	28.398361	57.052139	2.874341	14.000000	16.688980	19.858429	14.386475	0.028943	0.163852	1.467398
19	3.237062	6.481072	3.006891	2.000000	0.186127	37.969147	1.237061	0.000920	0.052437	1.488533
20	4.308352	8.621549	3.046536	2.000000	0.285553	34.322952	2.308350	0.000936	0.051857	1.527598
21	2.484143	5.018169	2.648895	2.000000	0.200459	27.466171	0.484131	0.003231	0.103049	1.181149
22	1.980471	3.983830	2.838953	1.000000	0.148060	28.852966	0.980469	0.001498	0.151314	1.419471
23	13.177022	26.381607	3.011832	6.000000	2.746017	19.975571	7.176758	0.006338	0.076969	1.518005
24	5.906501	11.826635	2.961140	1.000000	0.571426	26.166061	4.906494	0.001604	0.151314	1.541657
25	63.213623	127.148575	2.639084	57.000000	102.878418	27.383698	6.009766	0.080334	0.129523	1.197811
26	45.290390	90.611938	3.058171	33.000000	14.724701	32.887207	12.286621	0.012907	0.035540	1.522915
27	13.024018	26.058411	3.055106	4.000000	2.013031	23.626175	9.023926	0.003793	0.063693	1.548003
28	29.514572	60.627838	2.497097	15.000000	52.029785	15.268211	14.422119	0.079174	0.387577	1.313878
29	21.223801	42.533188	2.942909	6.000000	5.981308	21.887802	15.222412	0.011484	0.153672	1.525785
30	1.992432	3.987617	3.036511	1.000000	0.051997	78.666046	0.992432	0.000197	0.052537	1.518253
31	3.477543	6.962533	2.997240	1.000000	0.278854	28.307037	2.477539	0.001451	0.104199	1.530643
32	1.329346	2.663297	2.949425	1.000000	0.031976	84.615814	0.329346	0.000565	0.048394	1.427023
33	15.149013	30.437485	2.865583	6.000000	7.690567	14.076841	9.144531	0.024324	0.190193	1.484981
34	29.336380	59.173462	2.716838	7.000000	17.033615	20.459396	22.325195	0.027623	0.347598	1.493641

TABLE 4

STORM NO	STORMFLO	INTERFLO	RAPIDFLO	QINCH	INTERFLINCH	RAPINCH	TOTAL TIME	QFLO TO PEAK	QFLOAFTER PEAK
1	5.628342	5.607141	0.021201	0.001567	0.001562	0.000006	75.133362	3.461517	2.166824
2	10.738663	10.685075	0.053588	0.002991	0.002976	0.000015	81.719055	6.702942	4.035721
3	90.840500	77.133896	13.706604	0.025299	0.021482	0.003817	37.497070	58.618515	32.221985
4	0.624496	0.608575	0.015921	0.000174	0.000169	0.000004	7.611084	0.102419	0.522078
5	1.910767	1.847014	0.063752	0.000532	0.000514	0.000018	18.204346	0.530106	1.380661
6	4.716461	4.143235	0.573226	0.001314	0.001154	0.000160	14.918457	1.947220	2.769241
7	9.330338	9.022338	0.308000	0.002598	0.002513	0.000086	40.278809	7.540192	1.790146
8	27.389969	22.078445	5.311523	0.007628	0.006149	0.001479	36.407471	12.418488	14.971481
9	36.399902	32.919922	3.479980	0.010137	0.009168	0.000969	82.464355	1.024520	35.375381
10	1.685089	1.602720	0.082369	0.000469	0.000446	0.000023	14.087158	0.574066	1.111023
11	10.940155	9.813321	1.126834	0.003047	0.002733	0.000314	20.749512	7.123047	3.817108
12	0.323395	0.317387	0.006008	0.000090	0.000088	0.000002	7.954102	0.023643	0.299751
13	7.246262	6.767776	0.478485	0.002018	0.001885	0.000133	32.626709	2.197449	5.048813
14	3.776962	3.766162	0.010800	0.001052	0.001049	0.000003	57.176758	0.133688	3.643274
15	8.567810	8.358461	0.209349	0.002386	0.002328	0.000058	26.989014	3.808487	4.759323
16	108.277496	86.677582	21.599915	0.030155	0.024140	0.006016	35.973877	70.824631	37.452866
17	0.610332	0.377103	0.233228	0.000170	0.000105	0.000065	2.457031	0.190930	0.419401
18	16.688980	13.768891	2.920089	0.004648	0.003835	0.000813	28.386475	8.091278	8.597702
19	0.186127	0.170116	0.016010	0.000052	0.000047	0.000004	3.237061	0.103551	0.082576
20	0.285553	0.269664	0.015889	0.000080	0.000075	0.000004	4.308350	0.102419	0.183134
21	0.200459	0.155290	0.045169	0.000056	0.000043	0.000013	2.484131	0.151707	0.048752
22	0.148060	0.101863	0.046197	0.000041	0.000028	0.000013	1.980469	0.074757	0.073303
23	2.746017	2.598861	0.147157	0.000765	0.000724	0.000041	13.176758	1.172394	1.573624
24	0.571426	0.519085	0.052342	0.000159	0.000145	0.000015	5.906494	0.074757	0.496670
25	102.878418	90.216812	12.661606	0.028652	0.025125	0.003526	63.009766	91.159668	11.718750
26	14.724701	14.310994	0.413707	0.004101	0.003986	0.000115	45.286621	11.838181	2.886520
27	2.013031	1.955613	0.057418	0.000561	0.000545	0.000016	13.023926	0.467712	1.545319
28	52.029785	41.807632	10.222153	0.014490	0.011643	0.002847	29.422119	20.777908	31.251877
29	5.981308	5.307069	0.674239	0.001666	0.001478	0.000188	21.222412	2.259674	3.721634
30	0.051997	0.044921	0.007076	0.000014	0.000013	0.000002	1.992432	0.026096	0.025901
31	0.278854	0.252647	0.026207	0.000078	0.000070	0.000007	3.477539	0.051554	0.227301
32	0.031976	0.027922	0.004053	0.000009	0.000008	0.000001	1.329346	0.024049	0.007927
33	7.690567	6.718656	0.971911	0.002142	0.001871	0.000271	15.144531	3.587250	4.103317
34	17.033615	13.877348	3.156267	0.004744	0.003865	0.000879	29.325195	5.823593	11.210022

TABLE 5

SUMMARY OF STORM FLOW DATA

STORM NO	STORMFLO	%INTERFLO	%RAPIDFLO	% BEFORE PK	% AFTER PK	
1	5.628342	99.62	0.38	61.50	38.50	1
2	10.738663	99.50	0.50	62.42	37.58	2
3	90.840500	84.91	15.09	64.53	35.47	3
4	0.624496	97.45	2.55	16.40	83.60	4
5	1.910767	96.66	3.34	27.74	72.26	5
6	4.716461	87.85	12.15	41.29	58.71	6
7	9.330338	96.70	3.30	80.81	19.19	7
8	27.389969	80.61	19.39	45.34	54.66	8
9	36.399902	90.44	9.56	2.81	97.19	9
10	1.685089	95.11	4.89	34.07	65.93	10
11	10.940155	89.70	10.30	65.11	34.89	11
12	0.323395	98.14	1.86	7.31	92.69	12
13	7.246262	93.40	6.60	30.33	69.67	13
14	3.776962	99.71	0.29	3.54	96.46	14
15	8.567810	97.56	2.44	44.45	55.55	15
16	108.277496	80.05	19.95	65.41	34.59	16
17	0.610332	61.79	38.21	31.28	68.72	17
18	16.688980	82.50	17.50	48.48	51.52	18
19	0.186127	91.40	8.60	55.63	44.37	19
20	0.285553	94.44	5.56	35.87	64.13	20
21	0.200459	77.47	22.53	75.68	24.32	21
22	0.148060	68.80	31.20	50.49	49.51	22
23	2.746017	94.64	5.36	42.69	57.31	23
24	0.571426	90.84	9.16	13.08	86.92	24
25	102.878418	87.69	12.31	88.61	11.39	25
26	14.724701	97.19	2.81	80.40	19.60	26
27	2.013031	97.15	2.85	23.23	76.77	27
28	52.029785	80.35	19.65	39.93	60.07	28
29	5.981308	88.73	11.27	37.78	62.22	29
30	0.051997	86.39	13.61	50.19	49.81	30
31	0.278854	90.60	9.40	18.49	81.51	31
32	0.031976	87.32	12.68	75.21	24.79	32
33	7.690567	87.36	12.64	46.64	53.36	33
34	17.033615	81.47	18.53	34.19	65.81	34

APPENDIX 2

The Hydrograph Analysis Program Written in Fortran IV language

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0001            DIMENSION S(9000),HOUR(9000),QFLL(300),TS(300),TP(300),TE(300),
               2RS(300),RE(300),DR1(300),DR2(300),DT1(300),DT2(300),RP(300),
               3UP(300),DN(300),PERIM(300),A(300),PERFL(300),A2(300),ARISE(300),
               4AGLDN(300),BASE(300)
0002            DIMENSION QFLPK(300),QFPPK(300)
0003            DIMENSION TOTTM(300),QINCH(300)
0004            DIMENSION SUBFF(300),RFLL(300),SLBIN(300),RINCH(300)
0005            DIMENSION PIFLO(300),PRFLO(300),PQBPK(300),PCAPK(300)
          C  THE PROGRAM ACCOMODATES 300 STORMS.  IF A LARGER NUMBER OF STORMS IS
          C  ANTICIPATED, THE DIMENSION STATEMENT ABOVE SHOULD BE CHANGED, OR
          C  THE NUMBER OF DATA BEING ANALYZED AT ONE TIME SHOULD BE REDUCED.
0006            DO 7  J=1,9000
0007        7   S(J)=-1.0
0008            ENDS=-1.0
          C  IN THIS PROGRAM,S=STAGE.THE CONVERSION FROM STAGE TO CFS TAKES PLACE
          C  BELOW,UNDER'Q= ', AND 'RS(K)= '.CONVERSION CONSTANTS SHOULD BE CHANGED
          C  TO FIT THE WEIR BEING USED.
0009            READ (5,1,END=8)S
          C  THE FOLLOWING FORMAT STATEMENT MUST FIT THE FORMAT IN WHICH THE INPUT
          C  DATA FOR STAGE ARE PUNCHED.
0010        1   FORMAT (10X,12F4.3,22X)
          C  IF HYDROGRAPH READINGS ARE TAKEN AT INTERVALS OTHER THAN ONE HOUR,
          C  THEN A SEPARATE 'READ' STATEMENT SHOULD BE MADE.
0011        8   DO 2 J=1,9000
0012        2   HOUR(J)=J
0013            J=1
0014            K=1
0015        4   START=S(J)
0016            IF(S(J).LE.ENDS) GO TO 8001
0017        3   IF(S(J+1).GT.START) GO TO 100
0018            IF(S(J+1).LE.START) J=J+1
0019            GO TO 4
0020      100   WRITE(6,5) K
0021        5   FORMAT('1',50X,'TABLE 1'/15X,'STORM NUMBER',I4)
0022            TS(K)=HOUR(J)
0023            Q=1.522*(8.0**0.026)
0024            RS(K)=S(J)**Q*32.0
0025            WRITE (6,6) TS(K),RS(K)
0026        6   FORMAT(2X,'STORM BEGINS AT',F10.2,3X,'INITIALRUNOFF RATE IS',F12.6
               2/2X,'TIME BASEFLORATE RUNOFRATE   BASEFLO   TOTALFLO   STORMFLO%
               3 STORMFLO   INTERFLO   RAPIDFLO INTERFLORATE')
0027            U=0
0028            RC=0
0029            UCUM1=RS(K)
0030            DFLAF=0
0031            QFLO=0
0032            RP(K)=RS(K)
0033            TP(K)=HOUR(J)
0034            U2=0
0035            SUBFL=0
0036            RFLO=0
0037            UCUM3=RS(K)
0038            R1=S(J)**Q*32.0
0039            R2=S(J+1)**Q*32.0
0040      200   DIFR=ABS(R2-UCUM1)
0041            DIFT=HOUR(J+1)-HOUR(J)
0042            T=HOUR(J+1)
0043            H=SQRT(DIFR**2+DIFT**2)
0044            IF(H.LT.DIFR)H=DIFR
0045            IF(H.LT.DIFT)H=DIFT
0046            RC=(R2+R1)/2.0*DIFT+RC
0047            ALPHA=ATAN(DIFR/DIFT)
0048            BETA=(H*ALPHA-DIFR)/H
0049            IF(BETA.LE.0) BETA=0
0050            CSA=1.0+SIN(ALPHA)
0051            U=EXP(-CSA)*SQRT(DIFR*DIFT*TAN(BETA))
0052            UCUM2=U+UCUM1
0053            IF(R2.GT.RP(K))TP(K)=T
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          IF(R2.GT.RP(K))   RP(K)=R2
          IF(S(J+2).LE.ENDS) GO TO 8001
          R3=S(J+2)**Q*32.0
          DIFT2=HOUR(J+1)-HOUR(J)
          DIFR2=R2-UCUM3
          IF(DIFR2.LE.0) GAMMA=0.0
          IF(DIFR2.LE.0)      GO TO 15
          H2=SQRT(DIFR2**2+DIFT**2)
          GAMMA=H2/(DIFT2+3.0*DIFR2)
   15     U2=GAMMA*DIFR2
          UCUM4=UCUM3+U2
          IF(UCUM4.LE.UCUM2) UCUM4=UCUM2
          IF(UCUM4.GE.R2) UCUM4=R2
          IF(UCUM2-R2) 10,11,12
   10     DELAF=DELAF+(UCUM1+UCUM2)/2.0*DIFT
          PERC=100.0-DELAF*100.0/RC
          QFLO=RC-DELAF
          SUBFL=SUBFL+(UCUM3+UCUM4-UCUM1-UCUM2)/2.0*DIFT2
          RFLO=QFLO-SUBFL
          IF(T.EQ.TP(K)) QFLPK(K)=QFLO
          WRITE (6,13) T,  UCUM2,R2,DELAF,RC,PERC,QFLO,SUBFL,RFLO,UCUM4
   13     FORMAT(1X,F7.2,9F11.6)
          R1=R2
          R2=R3
          UCUM1=UCUM2
          UCUM3=UCUM4
          J=J+1
          IF(S(J).LE.ENDS) GO TO 8001
          GO TO 200
   11     DELAF=DELAF+(UCUM1+UCUM2)/2.0*DIFT
          PERC=100.0-DELAF*100.0/RC
          QFLO=RC-DELAF
          SUBFL=SUBFL+(UCUM3+UCUM4-UCUM1-UCUM2)/2.0*DIFT2
          SUBFF(K)=SUBFL
          RFLO=QFLO-SUBFL
          RFLL(K)=RFLO
          QFPPK(K)=QFLL(K)-QFLPK(K)
          WRITE (6,13) T,  UCUM2,R2,DELAF,RC,PERC,QFLO,SUBFL,RFLO,UCUM4
          RE(K)=R2
          TE(K)=T
          QFLL(K)=QFLO
          PIFLO(K)=SUBFF(K)*100.0/QFLL(K)
          PRFLO(K)=100.0/QFLL(K)*RFLL(K)
          PQBPK(K)=100.0/QFLL(K)*QFLPK(K)
          PQAPK(K)=100.0/QFLL(K)*QFPPK(K)
          K=K+1
          J=J+1
          IF(S(J).LE.ENDS)   GO TO 8001
          GO TO 4
   12     B1=(R2-R1)/DIFT
          B2=U/DIFT
          TIME=(-R1+UCUM1)/(B1-B2)
          TIMEX=HOUR(J)+TIME
          UCUM2=UCUM1+B2*TIME
          DELAF=DELAF+(UCUM1+UCUM2)/2.0*TIME
          XR=UCUM2
          RC=RC-(R2+XR)/2.0*(DIFT-TIME)
          PERC=100.0-DELAF*100.0/RC
           QFLO=RC-DELAF
          QFLL(K)=QFLO
          QFPPK(K)=QFLL(K)-QFLPK(K)
          SUBFL=SUBFL+(UCUM3-UCUM1)/2.0*TIME
          SUBFF(K)=SUBFL
          RFLO=QFLO-SUBFL
          RFLL(K)=RFLO
          WRITE (6,13)TIMEX,  UCUM2,XR,DELAF,RC,PERC,QFLO,SUBFL,RFLO,UCUM2
          RE(K)=XR
          TE(K)=TIMEX
```

```
0122            PIFLO(K)=SUBFF(K)*100.0/QFLL(K)
0123            PRFLO(K)=100.0/QFLL(K)*RFLL(K)
0124            PQBPK(K)=100.0/QFLL(K)*QFLPK(K)
0125            PQAPK(K)=100.0/QFLL(K)*QFPPK(K)
0126            J=J+1
0127            K=K+1
0128            IF(S(J).LE.ENDS)   GO TO 8001
0129            GO TO 4
0130       8001 WRITE(6,8110)
0131       8110 FORMAT('1',50X,'TABLE 2')
0132            WRITE(6,8003)
0133       8003      FORMAT(20X,'SUMMARY OF STORM DATA'/1X,' NO  TIME START TIME PE
               2AK TIMEEND  R START    R PEAK    R END   STORMFLO   INTERFLO    RA
               3PIDFLO')
0134            II=K-1
0135            DO 8100 J=1,II
0136            WRITE(6,8008)      J,TS(J),TP(J),TE(J),RS(J),RP(J),RE(J),QFLL(J),
               2SUBFF(J),RFLL(J)
0137       8008 FORMAT(1X,I3,9F10.4)
0138       8100 CONTINUE
0139            WRITE(6,8002)
0140       8002 FORMAT('1',50X,'TABLE3'/1X,'STORM',2X,'STORMFLO',29X,'TIME',18X,'P
               2ERIMETER/',4X,'RECESSION',' BASE LINE',3X,'RISING',3X,'FALLING'/1X
               3,'NO',3X,'BASE LINE',3X,'PERIMETER',4X,'TOP ANGLE',3X,'TO PEAK',5X
               4,'STORMFLO',2X,'LN(1+STORMFLO)',4X,'TIME',7X,'ANGLE',3X,'LIMB ANGL
               5E',1X,'LIMB ANGLE')
0141            DO 8200 J=1,II
0142            DR1(J)=RP(J)-RS(J)
0143            DR2(J)=RP(J)-RE(J)
0144            DT1(J)=TP(J)-TS(J)
0145            DT2(J)=TE(J)-TP(J)
0146            UP(J)=SQRT(DR1(J)**2+DT1(J)**2)
0147            DN(J)=SQRT(DR2(J)**2+DT2(J)**2)
0148            BASE(J)=SQRT((RE(J)-RS(J))**2+(TE(J)-TS(J))**2)
0149            PERIM(J)=UP(J)+DN(J)+BASE(J)
0150            A(J)=ATAN(DT1(J)/DR1(J))+ATAN(DT2(J)/DR2(J))
0151            A2(J)=ATAN((RE(J)-RS(J))/(TE(J)-TS(J)))
0152            ARISE(J)=ATAN(DR1(J)/DT1(J))
0153            AGLDN(J)=ATAN(DT2(J)/DR2(J))
0154            PERFL(J)=PERIM(J)/ALOG((QFLL(J)+1.0))
0155            TOTTM(J)=TE(J)-TS(J)
0156            WRITE(6,8009)      J,BASE(J),PERIM(J),A(J),DT1(J),QFLL(J),PERFL(J),
              2  DT2(J),A2(J),ARISE(J),AGLDN(J)
0157       8009 FORMAT(1X,I3,2X,8F12.6,2F9.6)
0158       8200 CONTINUE
0159            WRITE(6,8120)
0160       8120 FORMAT('1',50X,'TABLE 4')
0161            WRITE (6,8703)
0162       8703      FORMAT( 1X,'STORM NO   STORMFLO    INTERFLO    RAPIDFLO   QINC
               2H     INTERFLINCH     RAPINCH    TOTAL TIME   QFLO TO PEAK QFLOAFTER P
               3EAK')
          C    AINCH IS A CONSTANT FOR CONVERTING CFS INTO INCHES
0163            AINCH=3600.0*640.0*12.0/(5280.0**2)
          C    ACREK IS THE AREA OF THE WATERSHED BEING STUDIED IN ACRES
          C    THE VALUE OF 'ACREK' MUST BE CHANGED TO FIT THE WATERSHED
          C    BEING STUDIED.
0164            ACREK=3561.0
0165            DO 8720 J=1,II
0166            QINCH(J)=QFLL(J)*AINCH/ACREK
0167            SUBIN(J)=SUBFF(J)*AINCH/ACREK
0168            RINCH(J)=RFLL(J)*AINCH/ACREK
0169            WRITE (6,8700) J,QFLL(J),SUBFF(J),RFLL(J),QINCH(J),SUBIN(J),
               2RINCH(J),TOTTM(J),QFLPK(J),QFPPK(J)
0170       8700 FORMAT(1X,I3,5X,9F12.6)
0171       8720 CONTINUE
0172            DO 8600 J=1,II
```

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0173          8600 WRITE (7,8000) A2(J),ARISE(J),A(J),AGLDN(J),DT1(J),DT2(J),TOTTM(J)
                  2,DR1(J),DR2(J),QFLL(J),PERIM(J),PERFL(J),QINCH(J),TS(J),TE(J),
                  3RP(J),QFLPK(J),QFPPK(J),SUBFF(J),RFLL(J)
0174          8000 FORMAT(5F15.6/5F15.6/3F15.6,2F7.2/5F12.6,17X,'401')
0175               WRITE (6,8130)
0176          8130 FORMAT ('1',50X,'TABLE 5')
0177               WRITE(6,7001)
0178          7001     FORMAT(10X,'SUMMARY OF STORM FLOW DATA'/1X,'STORM NO',2X,'STORM
                  2FLO      %INTERFLO      %RAPIDFLO      % BEFORE PK   % AFTER PK')
0179               DO 7002 J=1,II
0180          7002 WRITE(6,7003) J,QFLL(J),PIFLO(J),PRFLO(J),PQBPK(J),PQAPK(J),J
0181          7003 FORMAT(1X,I3,5X,F13.6,4F13.2,I4)
0182          9999 STOP
0183               END
```


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BETHLAHMY, NEDAVIA

1972. Hydrograph analysis: a computerized separation technique. USDA Forest Serv. Res. Pap. INT-122, 19 p., illus.

Describes a computer program (Fortran IV language) designed to analyze hydrographs. Using only input data of stage and time, the program automatically determines the beginning and end of each event, analyzes each event with respect to all its hydrologic characteristics (including a partitioning of base flow, interflow, and rapid flow), and then prints a detailed analysis of each event and a series of summaries of all events analyzed.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)